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APPLICATIONS OF SPACE TECHNOLOGY TO THE STUDY OF DESERTIFICATION IN DEVELOPING COUNTRIES

Note by the Secretariat

1. The Working Group of the Whole to Evaluate the Implementation of the Recommendations of the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE 82), in the report on the work of its fifth session (A/AC.105/483, annex II), proposed that a few specific space applications studies should be carried out to demonstrate the potentials of space technology. The Working Group identified a number of possible subjects for such studies, including the subject of desertification, and proposed that information on some of those subjects might be provided as part of the United Nations efforts in conjunction with International Space Year (ibid., para. 6).

2. The Working Group noted that two such studies had been prepared by the Secretariat for the twenty-eighth session of the Scientific and Technical Subcommittee, a study on flood monitoring and control (A/AC.105/472) and a review of upper atmosphere studies for weather and environment monitoring (A/AC.105/477).

3. The report of the Working Group was adopted by the Scientific and Technical Subcommittee in its report on its twenty-eighth session (A/AC.105/483, para. 22), and the recommendations were endorsed by the Committee on the Peaceful Uses of Outer Space in its report on its thirty-fourth session 1/ and by the General Assembly in its resolution A/46/45 of 9 December 1991.

4. The present study has been prepared by the Secretariat in response to the request of the Working Group of the Whole. Its purpose is to review the applications of space technology for monitoring desertification and for managing land and water resources to maximize productivity in areas susceptible to desertification. The study is intended primarily for the benefit of countries that have not yet used space technology for this purpose but are interested in its potential benefits.

5. The study was prepared using a variety of national and international sources. The main sources are listed in the selected bibliography at the end of the study.

6. The following summary of the study appears in all the official languages of the United Nations. The full study, contained in the annex to the present document, is being distributed only in the language in which it was prepared (English) because of its technical character.

SUMMARY OF THE STUDY

7. The term "desertification" has been used in a variety of ways, generally referring to a decline in the biological productivity of land. The problem of desertification came to international public attention following the severe drought in the Sahelian region of West Africa from 1968 to 1973, and attention since then has continued to focus on semi-arid regions in Africa and elsewhere. The present report focuses on the processes leading to loss of agricultural productivity in the semi-arid zone of developing countries, but also considers briefly other land degradation processes.

8. The semi-arid zone is an extensive area of relatively low agricultural productivity. The study and monitoring of desertification in such areas, in order to be economically viable, must be low-cost, particularly since the dynamic nature of desertification processes makes repetitive monitoring necessary. Satellite data are ideal for monitoring desertification since they cover large areas repetitively at a very low cost per unit area compared to aerial or ground surveys. More detailed and supplementary information can be obtained as necessary using air or ground surveys, but a cost-effective system will make the maximum possible use of satellite data.

9. Variations in agricultural productivity depend on climate, the characteristics of the land and human activities. The variations include short-term fluctuations and long-term trends and can be either reversible or permanent. While concern focuses on long-term land degradation due to human activities, it is extremely difficult to separate long-term trends from short-term variations and to distinguish the effects of human activities from the effects of climatic variations. A major goal of desertification studies is to understand how natural changes and human activities are interrelated.

10. The primary application of satellite observations to desertification is the monitoring of vegetation condition. Because green vegetation absorbs red light and reflects infrared radiation, it is easily recognized on multispectral images against a background of soil or rock, which generally reflect more equally in the red and infrared. Because of these distinct spectral characteristics, it is possible not only to distinguish areas covered by vegetation from desert areas, but also to estimate the proportion of vegetation cover in semi-arid areas with sparse and scattered vegetation.

11. The technique for using satellite multispectral data for quantitative measurements of vegetation in semi-arid areas is called the normalized difference vegetation index (NDVI). It is the development of this technique which has made satellite data so effective for monitoring changes in biological productivity. The technique has been widely used both for monitoring natural vegetation for rangeland management and for assessing crop condition for agricultural production estimates. Data suitable for this purpose include high-resolution (20-80 m) remote-sensing data from the United States Landsat and French SPOT satellites and low-resolution (1-4 km) data from meteorological satellites.

12. Operational vegetation monitoring for rangeland management has been developed particularly in Kenya and Senegal with the assistance of the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization of the United Nations (FAO). The use of meteorological satellite data for vegetation monitoring has been combined with light aircraft sampling surveys for counting cattle, sheep, goats and human habitations, and detailed local ground studies of human, animal and plant ecology in order to study the overall human-animal-plant interactions in the semi-arid rangeland used by nomadic pastoralists. The resulting understanding of traditional land use practices is assisting in the development of livestock health and marketing programmes designed to protect the rangeland and improve productivity while respecting the traditional way of life.

13. The processes of wind and water erosion that contribute to desertification are generally not directly visible on satellite images, but indicators of susceptibility to erosion can be mapped effectively. Water erosion depends on slope, soil characteristics, vegetation cover and drainage patterns, all of which can be interpreted, directly or indirectly, from remote-sensing satellite images. From the maps of those features, a combined map of susceptibility to water erosion can be prepared for use in agricultural and land use planning. Similar procedures can be used for preparing maps of susceptibility to wind erosion. The effects of water erosion can sometimes be seen directly on satellite images in the form of sediment plumes carried by rivers into lakes or the ocean, and the effects of severe wind erosion can sometimes be seen in the form of enormous dust clouds carried out over the ocean.

14. In areas susceptible to erosion or other desertification processes, careful land use planning is essential to maximize sustainable production. The optimum use of land will depend on soil characteristics, geomorphology, drainage networks, climate, population density and social and economic factors. While remote sensing cannot provide all of this information, it can provide essential information, which can be combined with information from other sources into maps showing actual and potential land use for use in planning and decision-making.

15. In arid and semi-arid areas, the conservation of the limited water resources is economically vital. Remote sensing can be used to map the network of streams and rivers and to monitor the seasonal filling and drying

of lakes and reservoirs. An evaluation of the existing water resources and their use is essential to the planning of improved conservation and more efficient use of water resources.

16. Some arid and semi-arid areas have substantial groundwater resources, possibly remaining from times when the climate was more humid. While groundwater is not directly detectable by remote sensing, the geomorphology, drainage patterns, soil characteristics and vegetation patterns provide information on subsurface structures that may hold water. Maps of these visible features can be prepared and used for the preparation of a groundwater potential map to guide ground surveys and well digging. A programme in India has used remote sensing to substantially improve the success rate in well digging for village water supplies.

17. Deforestation is an important process of land degradation in many parts of the world. In many semi-arid developing countries, the sparse tree population is being severely reduced by the demand for fuel wood, a process that increases the susceptibility of the soil to both wind and water erosion. In more humid areas, deforestation is causing increased water erosion in hilly areas, and large-scale deforestation is believed to be contributing to the greenhouse effect. In areas of thick forest cover, forest clearing is generally easily visible on Landsat and SPOT images, while in sparsely wooded semi-arid areas the effects of tree cutting appear on satellite images as part of the general reduction in ground cover.

18. Data for the fight against desertification can be obtained not only from remote-sensing satellites, but also from meteorological satellites. Meteorological satellite data provide information on cloud distribution, cloud temperature and other meteorological factors, which can be used to estimate rainfall for such purposes as crop yield prediction and desert locust warning. Some meteorological satellite sensors also provide daily, low-resolution visible and infrared data for very cost-effective, frequent monitoring of vegetation condition.

19. The greenhouse effect, due to increased atmospheric levels of carbon dioxide and other gases, is expected to cause not only a general warming of the Earth, but also to change rainfall and cloud patterns. It is likely that some areas will become more humid and less susceptible to desertification while other areas will become drier and more at risk, but how those effects will be distributed is not yet understood. Some large-scale climate change effects, such as those due to the El Niño phenomenon and to large volcanic eruptions, are beginning to be understood, but much more research is needed to understand the processes of global warming and its effects on desertification.

20. Space technology for monitoring the global environment is developing rapidly. New satellites and sensors are being designed and launched, more powerful data-processing techniques are becoming available and new applications are being developed for use in maintaining and reclaiming areas susceptible to or affected by desertification, while increasing production to meet the needs of growing populations. That research and development will

require extensive cooperation between the space Powers and users, and between developed and developing countries. The control of global climate change in particular will require a concerted effort by all of the countries of the world.

Notes

1/ Official Records of the General Assembly, Forty-sixth Session, Supplement No. 20 (A/46/20), para. 31.

Annex

THE APPLICATIONS OF SPACE TECHNOLOGY TO THE STUDY OF DESERTIFICATION IN DEVELOPING COUNTRIES

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I. THE PROBLEM OF DESERTIFICATION

A. The concept of desertification

1. The term desertification has been used with a variety of meanings, and the appropriate definition is still a matter of dispute. In the narrowest sense, it can refer to the expansion or creation of barren deserts as a result of human activities, while in a broad sense it can refer to any decline in the biological productivity of land due to either human activities or natural climate change.

2. Desertification was brought dramatically to the attention of the world community when the Sahelian region of Africa was struck by severe and persistent drought from 1968 to 1973. The drought caused great hardship due to crop failures and to the decline in the natural vegetation needed to support livestock. In 1974, the United Nations General Assembly recognized the need for international cooperation to study and combat desertification, and in 1977 the United Nations Conference on Desertification was convened in Nairobi to consider the question.

3. The study of desertification has generally emphasized the problems of the semi-arid areas of the world, where subsistence is difficult in normal times and where a modest deterioration of conditions can mean disaster. Not only are the ecologies and economies of such areas more precarious, but such areas often have greater climatic variability than either wetter or drier areas. Some studies of desertification, however, have also examined declines in productivity in more humid regions due to such processes as waterlogging of soils and deforestation.

4. Desertification is a particularly critical problem in developing countries where population growth and the need for economic and social development require increases in the production of food and other agricultural products. In those countries, the deterioration of productive ecosystems poses an immediate and serious threat to human welfare. The need to increase production has intensified land use, often leading to excessive or inappropriate exploitation of less productive land and more fragile ecosystems, leading to declining productivity, which may further increase the pressure.

5. The relationship between ecological degradation and climate change continues to be a matter of study and debate. Some researchers have believed that real climate change, as distinct from short-term variations, is rare and that long-term land degradation is occurring as a result of excessive exploitation of vegetation and soil by cultivation and livestock. Other researchers have concluded that most of what is called desertification is a natural and reversible ecological response to natural climate variations. From either perspective, however, declines in production cause serious human distress, and there is a need to develop agricultural practices that maximize production on a sustainable basis within a highly variable climate.

6. The present study will focus on processes leading to a loss of land productivity in semi-arid developing countries, taking into account natural climate variability, land degradation caused by human activities, and the interactions between those two factors. The concerns raised more recently about global warming and its possible effects on desertification processes will also be considered.

B. The processes of desertification

7. A decline in land productivity, for either cultivated crops or natural vegetation, can be caused by either a change in climate or a change in soil conditions. Since climate is a naturally changing phenomenon, and since human land use practices evolve, land productivity depends on the dynamic interaction between the two forces. In the semi-arid zone, rainfall is the primary climatic factor limiting biological productivity, so a short-term or long-term decrease in rainfall is the simplest cause of a decline in productivity. When the climate is stable, human activities such as tree cutting, brush-burning, over-cultivation and overgrazing can cause a gradual loss of soil fertility, decreased water absorption and declining productivity.

8. The environmental variability of semi-arid regions has been dramatically illustrated by a recent satellite study of variations in vegetation in West Africa in the 1980s. A statistical analysis of vegetation patterns revealed by meteorological satellite imagery from 1981 to 1989 showed that the patterns were quite uniform for the Saharan regions and for the more humid regions south of the Sahel. The variability was strongly concentrated in an East-West band about 500 km wide with an average rainfall between about 500 and 1000 mm per year.

9. Most commonly, serious desertification in the semi-arid zone results from a combination of climate variation and land use changes. In the Sahelian region in the 1950s and early 1960s, relatively abundant and reliable rainfall combined with population growth caused the expansion of cultivation into land normally used as rangeland. When rainfall decreased and became more erratic from the late 1960s to the mid-1980s, the crops failed. The expansion of cultivation into the best grasslands had reduced the land available for grazing, resulting in more intensive grazing of a declining supply of natural vegetation. The reduction in vegetation cover increased wind erosion and water runoff, decreasing the absorption of water into the soil where it could remain available for plants for some time.

10. Natural vegetation serves a variety of productive purposes. Grass provides the main sustenance of livestock, shrubs reach deeper into the soil for moisture to provide browsing forage for livestock later in the dry season, and trees provide shade for humans and animals, branches for construction and firewood for cooking. All natural vegetation holds the soil together and breaks the force of wind and rain to prevent erosion and increase water absorption. And decaying vegetation provides organic matter to improve the fertility and water absorbing capacity of the soil.

11. For a given set of land use practices, a particular balance of types and species of vegetation will be most valuable. In many areas, traditional practices have evolved to maintain a useful and more or less stable balance of grass, shrubs and trees through such practices as seasonal grazing patterns and brush burning at the beginning of the dry season. Land productivity for human welfare is therefore not simply a matter of quantity of vegetation, but also of quality for a particular purpose. A process of desertification may be the replacement of a nutritious species of grass for grazing by a less nutritious species.

12. The structure and chemistry of the soil is a key factor in biological productivity and determines the water and energy balance. When vegetation is reduced and the soil is exposed to the direct impact of the brief but intense rains that are common in semi-arid areas, the organic matter will be quickly mineralized and the soil structure will be broken down, leaving a solid crust to be baked by the sun into an impermeable layer which prevents rain from infiltrating. As more water is lost to runoff and surface evaporation, the soil moisture usable by plants will decline, and the water level in wells may fall. The increased runoff will carry off the topsoil, particularly where a layer of dust has been created by human or animal traffic, removing the most fertile soil with the best structure for supporting vegetation. Loose, fine-textured dirt and dust can also be carried away by the wind in dust storms. The remaining bare soil is essentially infertile, with poor structure and water absorbing and retaining capacity. All these changes constitute a shift toward a more hostile environment for plants, with the result that vegetation responds less well to rain and dies off at an increasingly early stage of drought.

13. When soil erodes, the combined action of water and wind tend to remove the finer and more fertile clay and silt components, leaving behind the course and infertile sand. Wind erosion often starts with the movement of coarse particles, then progresses downwind with increasing severity as bouncing particles knock other particles into the air in a kind of chain reaction. Finer materials are lifted into the air and carried away over long distances as dust; coarser sandy materials drift over the surface until they are trapped by plants in accumulations as hummocks and small dunes. A further harmful effect of high-velocity sand drift may be the destruction of young crops by the blasting impact of moving sand. In addition, fine airborne particles may carry soil-borne diseases, irritate the respiratory tracts of humans and animals, cause wear on machine parts and reduce visibility.

14. Once the processes of desertification are set in motion, they can become self-perpetuating. This can occur where patches of soil are stripped of vegetation, for example near watering points or other places where livestock tend to congregate, and drifting sand destroys more vegetation, exposing more bare soil to wind and water erosion. As the degraded area expands, it becomes ever more difficult and more expensive to reclaim, with the costs of reclamation continually rising until the stark equilibrium of extreme desert is reached and the land has for all practical purposes passed beyond hope of rehabilitation.

15. While climate is generally taken as an independent factor that can cause desertification in interaction with land use practices, it is also possible that land use practices and desertification

can have effects on the climate. As vegetation cover is lost and the soil is mineralized, the surface become lighter in colour, reflecting more sunlight and absorbing less. The increased runoff of rain and the decreased evapotranspiration by plants also changes the local climate. Wind erosion puts more particles into the air affecting atmospheric energy balance and moisture condensation patterns. How those phenomena change rainfall patterns or other important climate conditions, however, is not well understood.

16. The warm temperatures and sunny skies in semi-arid areas can make them very productive if water is available for irrigation, but irrigation can also lead to problems in maintaining soil fertility. Groundwater in dry areas may contain high concentrations of dissolved salts or other minerals. When the groundwater is used for irrigation, the water evaporates or is absorbed by the crops, leaving accumulations of salts on or near the surface. If there is an impermeable layer of soil or rock near the surface, a layer of concentrated saline solution can develop leading to both salinization and waterlogging.

C. The geography of desertification

17. Desertification is sometimes thought to be a problem that concerns just a few countries. In fact, more than one third of the earth's surface is arid or semi-arid and supports about 18 per cent of the world's population. It has been estimated that some 30 million square kilometers, 19 per cent of the earth's land surface, is potentially threatened with desertification, including areas in two-thirds of the countries of the world. There is concern that a significant portion of the world's arable land is being lost to desertification, and that such losses, during a period of unprecedented population growth and increased demands for food, could be disastrous.

18. In Africa, concern over desertification has focused on the Sudano-Sahelian zone south of the Sahara, which was subject to a series of very dry years from 1968 to 1973, followed by a few years of more normal condition, but with a return to very low rainfall in the early and mid-1980s. Throughout the region, there has been substantial degradation of vegetation and soil due to cultivation practices and grazing pressures that could not be sustained under the existing environmental conditions. The increasing demand for fuel and food that has accompanied the rapidly growing population puts steadily increasing pressure on the increasingly fragile resources. Lake chad declined in size and the water levels in the Niger and Senegal rivers fell. In Djibouti, Somalia, Ethiopia, Kenya and Uganda, salinization of irrigated land and desertification of rain-fed farming are common. In the more humid regions of West and Central Africa, including Guinea, Benin, Nigeria and Cameroon, land degradation is occurring where population pressures are leading to excessive tree cutting for fuel wood and overgrazing, leading to soil deterioration and erosion.

19. Of the countries of North African, 80 per cent of the land area consists of the Sahara Desert, and much of the rest is semi-arid. In many areas, grassland has decreased as a result of overgrazing, and water and wind erosion have exacerbated the damage. In Tunisia, more than half of the rangelands have been subject to desertification, and about 10 per cent of those are

considered beyond reclamation. The situation is similar in Morocco. Deforestation is common as a result of fuel-wood consumption and clearing for agriculture in all of the countries of the region. Soil erosion by both wind and water is occurring in areas where rainfed agriculture has been abandoned. In Egypt, which is mostly desert except for the narrow Nile Valley, completion of the Aswan-high dam and rising ground-water levels have caused waterlogging and salinization of irrigated land in some areas. The dam has also reduced the alluvial soil carried by the Nile, thus reducing the productivity of land downstream. Salinization has also affected substantial areas in Sudan.

20. In southern Africa, desertification is severe in places around the Kalahari desert. In the southwestern part of Botswana and Namibia, sand dunes have been encroaching on agricultural areas and soil fertility has been lost due to water and wind erosion. In Malawi, Zimbabwe and Zambia, deforestation is occurring due to increasing demand for fuel-wood for processing tobacco leaves. In densely populated areas in southern Zimbabwe and northern Namibia, topsoil erosion has been a serious problem as a result of fuel-wood collection, cultivation and overgrazing.

21. In China, more than half of the land area is arid or semi-arid, and areas in the northwestern part of the country are undergoing severe desertification. Population pressure results in intense use of land, even in the dry areas, and much topsoil has been lost due to erosion caused by the persistent winds. Destruction of vegetation for fuelwood, overgrazing and agricultural clearing have contributed to desertification.

22. In India, 12 per cent of the land is arid, and the large and rapidly growing population has been putting increasing pressure on that area and the surrounding semi-arid area. Wind erosion and remobilization of stable dunes as a result of overgrazing, cultivation and development activities are accelerating desertification. Salinization and waterlogging are important problems in irrigated agricultural areas. In Pakistan, there is severe desertification in low mountain areas in the western and northern parts of the country. Those areas are part of the watershed of the Indus River, and deforestation and overgrazing have destroyed vegetation over large areas and have caused severe erosion. Waterlogging and salinization are major problems on irrigated farmland.

23. West Asia has a long history of intensive cultivation and grazing, and desertification has been a long-term problem throughout the region. About two-thirds of the cultivated lands in the region show severe desertification. Rain-fed farming areas in the semi-arid and semi-humid region have experienced substantial wind erosion during the fallow season. Water erosion is a major problem on slopes in Jordan and Yemen, and waterlogging and salinization have been problems in irrigated lands, especially in southern Iraq.

24. In Mexico, desertification is an important problem in rain-fed farming areas, particularly on slopes as a result of wind erosion. Salinization of irrigated land and desertification of arid grassland are also problems. In Brazil, ecosystems in the semi-arid Nordeste region, which makes up about 18 per cent of the area of the country, have been disturbed by overgrazing, brush

burning and consumption of fuelwood. In Peru, salinization is occurring on irrigated farms along the rivers crossing the coastal deserts. In Chile, overgrazing and slope cultivation are a cause of desertification in the semi-arid coastal mountains. In Argentina, degradation of vegetation is resulting from overgrazing and agricultural clearing in arid areas.

25. Among the developed countries, Australia and the United States have extensive arid and semi-arid regions. Since the 19th century, rangelands and croplands have been developed in arid and semi-arid areas, resulting in soil degradation in some areas. Salinization of irrigated croplands and wind erosion of rain-fed agricultural land and rangeland have been continuing problems.

D. Global climate change

26. While desertification is an immediate problem for the inhabitants of the affected areas, it can also affect people living in other parts of the world. Deserts affect the global radiation budget, heat transportation, weather patterns and the hydrological cycle, and through these regional and global processes, climate changes in one area can affect distant areas. These large-scale processes and interrelationships are not yet well understood, and much more research is needed on climatic variations that affect desertification and the effects of human activities on those variations.

27. Since about the 1960s, there is evidence that weather patterns in many parts of the world have been more unstable than they were in previous decades. This increased variability in weather patterns is an important climate change in itself, and may indicate increasing climate change to come.

28. Global warming as a result of the greenhouse effect due to the increase in atmospheric carbon dioxide and other trace gases is expected not only to produce a general warming, but also to change the global patterns of rainfall. According to a study by the experts of the Intergovernmental Panel on Climate Change (IPCC), the theoretically expected temperature increase in the absence of remedial action would be about 1°C by the year 2025. However, this is merely a global average, and local changes may be substantially greater. Research is underway on the expected climate changes on a regional basis, but much work remains to be done before the climate models can be considered reliable with respect to regional weather patterns.

29. The study of global warming and other sources of climate change requires historical research as well as current observations. Natural traces of historical changes are particularly well preserved in arid and semi-arid areas due to the very low level of biological and hydrological activity. Such features as sand dunes, sedimentary deposits, traces of water erosion and groundwater deposits can provide evidence relating to the climate hundreds or thousands of years ago. In the Sahara, for example, radioactive dating of underground water indicates the times in the past when the climate was more humid and underground aquifers filled up. Research on the

history of deserts and climate change is essential for testing the theoretical models of climate change that are needed to predict the future and to take protective actions.

II. SPACE TECHNOLOGY AND DESERTIFICATION

A. Monitoring desertification from space

30. Regular and detailed monitoring of environmental conditions throughout the world is essential if desertification is to be understood and combatted while maximizing productivity for development. The remote sensing and satellite data that is available for the last two decades constitute both irreplaceable historical data and very cost-effective current data for assessing the magnitude, the extent, the processes and the effects of desertification.

31. Cost considerations are particularly important in arid and semi-arid areas since the relatively low productivity of the land cannot sustain expensive monitoring. Since such areas support only sparse and scattered populations, it is difficult to operate and maintain enough observing stations on the ground in many areas, and it may be difficult to maintain trained technicians in such areas for making careful systematic observations. Satellites may be very expensive to build and launch, but once in orbit the costs of receiving and processing the data are quite modest compared with alternative sources of data. Data from meteorological satellites in particular is made available by the launching countries and agencies without any charge for satellite operations or data processing.

32. In general, the cost of acquiring and interpreting geographical data over large areas is lowest for satellite data, intermediate for aerial surveys, and highest for ground surveys. The most cost-effective approach will therefore use satellite data whenever possible, aerial surveys for providing additional detail as required and for resolving ambiguities in the interpretation of the satellite data, and ground surveys for data that cannot be acquired in any other way. Among the different types of satellite data, meteorological data is less expensive than remote sensing data, so repetitive coverage of large areas should be done with meteorological data whenever possible.

33. Monitoring of desertification requires good base maps of the area in question showing the permanent features, such as topography and geology, and the slowly changing features such as soils and drainage. Those base maps can be compiled from high-resolution satellite remote sensing data, from existing aerial photography and ground survey data where they exist, supplemented by new aerial photography and ground surveys where necessary. Studies of historical data on climate and land use are also important.

34. The detailed base maps can then be used for monitoring changes with reference to the conditions at the time of the baseline survey and with respect to historical variations. The frequency of data acquisition for change monitoring will depend on the dynamics of the phenomena in question. Land use patterns, deforestation and agricultural clearing could be

surveyed every few years, or at most annually, using remote sensing satellite data. Monitoring surface water, crop conditions and rangeland condition might require coverage a few times a year, while rainfall and temperature would need to be monitored daily or even several times per day.

35. Satellite data is very well suited for monitoring changes since the sensors, coverage patterns and data formats remain constant for many years. Thus imagery acquired on different dates can be relatively easily compared. For some purposes such as rangeland monitoring, the high resolution offered by aircraft or ground surveys may be a disadvantage since the details can interfere with the analysis of the broad patterns. Similarly, for monitoring rainfall, the highly variable and localized nature of rainfall in arid and semi-arid regions mean that data from ground raingauges, while quantitatively accurate, may represent only a very small area, while satellite images will show the distribution of rain-bearing clouds over the entire area of interest. Detailed ground data is nonetheless useful for calibrating and checking the satellite interpretations.

36. In addition to the frequency of observation, the timing of the observations with respect to seasonal changes can be important. For some phenomena that change slowly or not at all, it may still be useful to obtain two or more sets of data covering different seasons. For example, while geological structure does not change with the seasons, it may nonetheless be useful to use imagery from the end of the dry season, when vegetation is minimum, for mapping surface structure, imagery from early in the dry season for mapping shallow subsurface structures that are reflected in persistent soil moisture, and imagery from the growing season to reveal geochemical factors that are indicated in vegetation patterns.

37. For the most rapidly changing environmental variables such as rainfall, geostationary meteorological satellites provide low-resolution observations at about 30 minute intervals throughout the day and night. Those data can be processed and averaged or integrated by computer to estimate rainfall or other factors over periods of days, weeks or other intervals.

38. In addition to land and atmospheric observations, comprehensive studies of the causes and effects of desertification will also require ocean observations. Ocean currents and temperature patterns, such as the El Niño phenomenon, affect rainfall and other weather patterns over large areas. Meteorological satellites can also be used for observing sea-surface temperature.

39. Remote sensing and meteorological satellites thus provide new and unique tools for monitoring desertification. The technologies and methods for interpreting the data and using the information are still young, however, and are still evolving rapidly. Resource and environmental management programmes throughout the world have been established on the basis of other information-gathering methods, and it may take some time to integrate the new technologies into existing institutions and procedures. There is therefore great potential for increasing and improving the use of satellite observations for monitoring desertification and understanding climate change on both the global and the local scale.

B. Satellite systems for monitoring desertification

40. Since the launch of the first Landsat satellite in 1972, satellite remote sensing data has been available on a worldwide basis. In 1986, the first of the French series of SPOT satellites was launched. These two series of satellites provide high-resolution data using multispectral scanners operating in the visible and infrared spectral bands. The Landsat satellites carry the Multispectral Scanner (MSS) system providing four spectral bands of data with 80 m resolution and the Thematic Mapper (TM) system providing seven spectral bands with 30 m resolution. The SPOT satellites carry a High Resolution Visible (HRV) sensor with three spectral bands and 20 m resolution, with the option of combining the three bands into panchromatic data with 10 m resolution. The satellite orbits provide regular coverage of all parts of the Earth other than regions immediately around the poles, with a coverage cycle of 16 days for Landsat and 26 days for SPOT. The Landsat satellites also provide thermal infrared data indicating ground temperature.

41. The data from the electronic multispectral sensors are transmitted to the ground in digital form as they are acquired. The data transmitted from the satellites is processed either into magnetic tape form suitable for computer analysis or into image form suitable for photointerpretation. Since the satellite sensors are not sensitive to blue light which is strongly scattered by the atmosphere, but are sensitive to infrared radiation, colour images produced from the data do not represent the true colours, but are "false colour" images in which the infrared radiation reflected from the ground is generally represented by red on the image. Due to the spectral characteristics of vegetation, in particular its high reflectance in the infrared band, the false colour images are particularly well suited for monitoring the condition of vegetation in semi-arid areas.

42. Other remote sensing satellites providing data that can be used for desertification monitoring include the Japanese Marine Observation Satellite (MOS), the first of which was launched in 1987, carrying the four-band Multispectral Electronic Self-Scanning Radiometer (MESSR) with 50 m resolution and the four-band Visible and Thermal Infrared Radiometer (VTIR) with 0.9 km resolution.

43. In 1991 two satellites equipped with radar mapping systems were launched, ERS-1 (Earth Resources Satellite) by the European Space Agency, and Almaz by the Union of Soviet Socialist Republics. The radar systems provide useful data for mapping geological structure, for mapping soil characteristics including soil moisture, for forest mapping and for acquiring data under cloudy conditions. The Japanese Earth Resources Satellite (JERS), scheduled for launch in 1992, will carry a radar system as well as a multispectral scanner, and the Canadian Radarsat, scheduled for launch in 1994, will carry a radar system.

44. Meteorological data is provided by the polar-orbiting satellites of the United States NOAA series and the USSR Meteor series, and by the geostationary satellites of the United States Geostationary Operational Environmental Satellite (GOES) series, the European Meteosat series,

the Japanese Geostationary Meteorological Satellite (GMS) series and the Insat series. All of those meteorological satellites produce observations of cloud distribution and cloud temperature which can be used for estimating rainfall and as data for weather forecasting. The geostationary satellites remain fixed over the same spot and provide images of about a third of the globe every 20 to 30 minutes, allowing continuous monitoring of cloud distribution. The NOAA satellites, in addition to providing cloud data, carry the four-band Advanced Very High Resolution Radiometer (AVHRR), which provides useful imagery of the ground with 1 km resolution for broad vegetation monitoring.

45. A variety of remote sensing and environmental satellites are planned for launch in the 1990s, with particular emphasis on environmental monitoring. These include a number of satellites as part of the United States Earth Observation System, the Japanese Advanced Earth Observation Satellite and the United States/Japan Tropical Rainfall Measuring Mission. Those experimental satellites will undoubtedly provide new capabilities for monitoring factors relating to desertification.

46. While the various satellites pass over all areas of the world on a regular basis, the availability of data depends on facilities for receiving and processing the data transmitted by the satellite. The satellites transmit the data as they are acquired to any ground station within view of the satellite, which means that a ground station can receive data for an area about 2500 km in radius around the station. Data for areas not covered by a ground station can be recorded on board the satellite for later transmission or can be transmitted via a relay satellite to a central receiving station. However, due to limited on-board recording capabilities and the limited availability of relay satellite capacity, areas not covered by local ground stations generally have less data available than areas that have ground stations. Currently some 18 countries covering most of the world operate stations for receiving data from Landsat, SPOT and MOS satellites, but most of Africa is not covered by any of those stations. The lack of a local receiving station particularly limits applications like environmental monitoring that require frequent coverage and rapid availability of data.

III. APPLICATIONS IN DEVELOPING COUNTRIES

A. Natural vegetation monitoring and rangeland management

47. The most general form of desertification monitoring has been based on remote sensing of natural vegetation, since land degradation is most readily identified through the resulting reduction in vegetation. The high reflectance of vegetation in the infrared band and its low reflectance in red light generally allow a clear distinction between vegetation and the soil or rock background. Soils and rocks generally have similar reflectances in the red and infrared, hence the difference between the infrared and the red measurements is therefore an indicator of the presence of vegetation. Using computer processing for quantitative analysis of the data, it is possible not only to distinguish areas covered by vegetation from desert areas, but also to

estimate the proportion of vegetation cover in semi-arid areas with sparse and scattered vegetation.

48. The technique for using satellite multispectral data for quantitative measurements of vegetation, called the normalized-difference vegetation index (NDVI), was developed in the mid-1980s for studying the Sahelian drought. It was the development of this technique which has made satellite data so effective for monitoring changes in biological productivity. The technique has been widely used both for monitoring natural vegetation for rangeland management and for assessing crop condition for agricultural production estimates. Data suitable for this purpose include high-resolution (20-80 m) remote sensing data from the United States Landsat and French SPOT satellites and low-resolution (1-4 km) AVHRR data from NOAA meteorological satellites.

49. The use of remote sensing data for change monitoring is complicated by the fact that differences between images can be caused by factors other than differences in the land surface conditions, including changes in sensor calibration, changes in illumination as a function of season or atmospheric conditions, and changes in image processing. Furthermore, even when the differences are due to ..e vegetation, they may be due to seasonal or climatic differences or to human activities as well as to land degradation, and may be a temporary disturbance or a long-term degradation. The normalized-difference approach, using spectral band differences and ratios, overcomes some of these problems, but efforts should be made to ensure that the image processing provides comparable data. When true differences are found, they must be interpreted in conjunction with climate data and ground sampling.

50. Operational vegetation monitoring for rangeland management has been developed particularly in Kenya and Senegal with the assistance of the United Nations Environment Programme, the United Nations Sudano-Sahelian Office and the Food and Agriculture Organization (FAO) of the United Nations. The use of meteorological satellite data for vegetation monitoring has been combined with light aircraft sampling surveys for counting cattle, sheep, goats and human habitations, and detailed local ground studies of human, animal and plant ecology in order to study the overall human-animal-plant interactions in the semi-arid rangeland used by the nomadic pastoralists. The resulting understanding of the traditional land use practices is assisting in the development of livestock health and marketing programmes designed to protect the rangeland and improve productivity while respecting the traditional way of life.

51. While satellite data cannot be used to count livestock, the high-resolution SPOT data, as well as aerial photography, does reveal the paths regularly used by the animals. The data has clearly shown in particular the severe reduction in vegetation that often occurs near sources of water, and the patterns of animal movements to and from the sources. Such observations indicate that attempts to increase livestock production by developing new sources of drinking water often do more harm than good by attracting more animals than the vegetation can sustain.

52. The carrying-capacity of rangeland depends not just on the quantity of natural vegetation, but also on its quality as livestock forage, which cannot be determined from satellite data. For

estimating carrying-capacity, satellite data is used to delimit areas of homogeneous vegetation, and ground sampling is then used to determine the proportions of the different species of vegetation within each of the homogeneous areas.

53. In planning land use to prevent desertification and to reclaim degraded areas, it is important to determine the susceptibility of the land to various forms of degradation. Areas susceptible to wind erosion, for example, have been mapped using Landsat Thematic Mapper data as a source of information on surface morphology, soil type, vegetation patterns and human activities. Each of these factors was mapped independently from the satellite images, and the four factors were then combined into one erosion susceptibility map. In cases of severe and large-scale wind erosion, dust plumes can be observed on remote sensing and meteorological satellite images, particularly when they are carried out over the ocean. The heavy particulate aerosol haze, which can be an obstacle to remote sensing interpretation of ground features, can be evidence of surface erosion.

54. The pressure of livestock on rangeland may be increased not only by greater numbers of livestock, but also by the extension of cultivation into range areas, excluding livestock from the most productive areas. In areas of population growth, and in times of abundant rainfall, agriculture will often be extended into previously uncultivated rangeland. While this may not pose a problem under those favourable conditions, in subsequent years of lower rainfall, the limited forage in the remaining rangeland will result in overgrazing of the rangeland. The crops in the marginal land are likely to fail, exposing the land to erosion. In the Sahelian region of West Africa, there was substantial expansion of cultivated areas during the relatively humid 1950s and early 1960s, a development that contributed to the hardships caused by the droughts from the late 1960s to the mid-1980s. An essential part of land management in semi-arid areas is therefore the monitoring and management of agricultural cultivation, taking into account the variations in rainfall.

55. Deforestation is an important process of land degradation in many parts of the world, both semi-arid and humid. In many semi-arid developing countries, the sparse tree population is being severely reduced by the demand for fuelwood, a process that increases the susceptibility of the soil to both wind and water erosion. In more humid areas, deforestation is causing increased water erosion in hilly areas, and large-scale deforestation is believed to be contributing to the greenhouse effect. In areas of thick forest cover, forest clearing is generally easily visible on Landsat and SPOT images, while in sparsely wooded semi-arid areas, the effects of tree cutting appears on satellite images as part of the general reduction in ground cover.

56. Some experimental work has been done on the use of microwave systems for monitoring vegetation in semi-arid areas. The observations indicate that the radar reflection does not depend on green vegetation but on the larger structures of shrubs and trees and on surface roughness in the absence of woody vegetation. While the usefulness of such observations is not yet clear, it appears that microwave systems could provide a useful complement to multispectral data.

B. Crop monitoring and drought warning

57. Crop yield estimation using remote sensing is very similar to the monitoring of natural vegetation. Remote sensing satellite observations of vegetation using the normalized-difference vegetation index technique are combined with environmental measurements such as rainfall, evaporation, soil moisture, temperature and solar radiation in a model of plant growth to estimate productivity.

58. In Niger, for example, in cooperation with France, a model of millet production was developed using remote sensing data. The model provides estimates of total biomass production as a function of solar radiation, atmospheric conditions, the efficiency with which the crop absorbs radiation at a particular stage of growth and the efficiency with which the crop converts radiation energy into plant material. The remote sensing vegetation measurements are used primarily to estimate the condition of the crop and hence its ability to absorb radiation and convert it into plant material. Application of the model in Niger indicated that it could estimate yield to an accuracy of about ten per cent.

59. Stress in crops that reduces yield as a result of drought, disease, insects, salinity or nutrient deficiencies generally appears in remote sensing images as a contrast in tone between healthy and stressed plants due to diminished photosynthetic activity, changes in leaf anatomy, or changes in the canopy owing to curling, wilting and leaf attitude. Temperature measurements using thermal infrared observations can also be used to indicate stress, since high temperatures can both directly reduce growth and increase evaporation, creating stress as a result of lack of moisture. The reduced evapotranspiration further increases the temperature of the plants further limiting growth.

60. Remote sensing is also an effective tool for identifying possible outbreaks of pests such as desert locusts, various grasshoppers and army worms, which can devastate agricultural crops and natural vegetation. Monitoring rainfall and increases in vegetation in the breeding grounds of the pests can be used to identify environmental conditions that favour their multiplication, providing early warning of an outbreak and allowing time to prepare control measures.

61. In arid and semi-arid areas, rainfall is generally the limiting factor for plant growth and therefore determines the productivity, whether for crops, natural vegetation, or livestock. Rainfall monitoring is therefore central to monitoring productivity and separating natural changes from changes due to human activities. Rainfall measurements are also essential to predict crop failures or problems in sustaining livestock. However, in extensive arid or semi-arid regions, it is difficult to monitor rainfall patterns by ground observation since rainfall is highly variable in both space and time and raingauges are difficult to monitor and maintain. Raingauge data is also difficult to interpret since it is often representative of only a very small area. Ground weather radar can be used to observe rainfall over larger areas, but coverage of a large area would be prohibitively expensive for most countries. Scattered raingauges and weather radar systems, however, can be extremely valuable for calibrating satellite data interpretation.

62. Several methods have been developed and tested for estimating rainfall from meteorological satellite data. The frequent data from geostationary meteorological satellites is particularly useful for rainfall estimation, and the low resolution simplifies data processing. While precipitation below clouds cannot be directly observed by satellite sensors, the existence and intensity of rain can be estimated from observations of cloud-top characteristics in the visible, thermal infrared or microwave wavelengths. From repetitive observations at visible and thermal infrared wavelengths, rain probability indicators are derived, such as cold-cloud-duration, cloud-line growth, cloud-edge temperature gradient, and cloud threshold-temperature excess. These indicators are then used in conjunction with a model of rain generation, taking into account local topography, latitude and seasonal effects.

63. In the visible spectrum, images can be interpreted in terms of cloud type and brightness, which are related to cloud thickness, which in turn is related to the probability of precipitation. Thermal infrared images are used for the estimation of cloud temperature, which depends upon cloud altitude. The higher the cloud, the colder its top, and the more rainfall it is likely to produce.

64. Microwave radiation passes through clouds, but is somewhat scattered and reflected by the larger droplets of rain. Microwave observations by radar or passive microwave radiometers may therefore provide some indication of precipitation below clouds. However, these technique have not yet been developed to an operational stage and need further research. The Tropical Rainfall Measuring Mission, a satellite designed for direct radar observations of tropical rain, is being planned as a cooperative project between the United States and Japan to develop that technology further.

65. While deficient rainfall is the essential cause of agricultural drought, there is no simple relation between total rainfall and agricultural production. Crop condition depends critically on the distribution of rain through the growing season as well as on the amount, and a dry spell during a critical growth stage can result in severe crop failure even if the rainfall for the year or the season as a whole is normal. Excess rain during critical periods can also reduce production. An assessment of the effect of a particular distribution of rainfall on crop production therefore requires a knowledge of the growth pattern of the crop. An effective crop inventory and crop-failure warning system will therefore include the use of remote sensing satellite data to monitor crop area and condition, meteorological satellite data to monitor and predict rainfall, and a knowledge of plant growth patterns and cultivation patterns for the area in question.

66. Since 1975, the FAO has been developing satellite remote sensing techniques to improve the surveillance and forecasting capabilities of FAO's Global Information and Early Warning System. The primary target of that effort is Africa, and a system called the Africa Real-Time Environmental Monitoring Information System (ARTEMIS) has been developed through cooperation between FAO, NASA's Goddard Space Flight Center in the United States, the Universities of Reading and Bristol in the United Kingdom, and the National Aerospace Laboratory (NLR) in the Netherlands. The ARTEMIS system uses hourly thermal-infrared cloud

observations from the European geostationary Meteosat satellite and daily images from the Advanced Very High Resolution Radiometer (AVHRR) data on the United States NOAA satellites. A similar technique has been developed by the United States Agency for International Development for a Famine Early Warning System for use at the AGRHYMET Centre in Niamey.

67. In the ARTEMIS system, the Meteosat thermal-infrared data are used to estimate rainfall, based upon the linear relationship between the vertical extent of a cloud, which is determined by the temperature of its top, and the amount of rainfall which falls from the cloud. Daily cold-cloud-duration maps are produced by integrating hourly Meteosat data, using cloud-top temperature thresholds determined for specific geographic regions and seasons. Ten-day estimated rainfall maps are generated from ten daily cold-cloud-duration maps using linear regression relations. Monthly estimated rainfall maps are then produced by integrating three ten-day maps. The maps have a resolution of about 7 km and cover Africa and West Asia.

68. NOAA AVHRR data are used to estimate the vegetation. First cloud-covered areas are identified using thermal infrared or visible data and eliminated. For the cloud-free areas, the amount of vegetation is estimated using the normalized-difference technique. By combining daily data for ten-day periods, cloud-free coverage of the entire area of interest can generally be obtained, and vegetation index maps are generated. A monthly vegetation-index map is generated by combining three ten-day maps. ARTEMIS produces vegetation maps of the West African desert locust breeding areas at a resolution of 1 km, and vegetation maps of Africa, Southern Europe, and West and Southwest Asia at a resolution of 7 km.

69. From the ARTEMIS office at FAO in Rome, the rainfall and vegetation maps are sent to offices at regional and national levels. The FAO Remote Sensing Centre, in cooperation with the European Space Agency and the International Telecommunications Satellite Organization (INTELSAT), has been developing the Diana satellite communications system, based on low-cost micro-computer technology, to transmit the images to users. The Diana system will allow high-speed, two-way transmission of data and information, including facsimile transmission of documents and maps, character-coded transmission of text documents, and data transmission of digital images in raw or processed form from FAO Headquarters to micro-computer-based receiver terminals at regional and national levels. Through the Diana system, current satellite-derived information can be rapidly provided to regional and national services concerned with food security and locust control.

70. In India, droughts are a major threat to the delicate balance of food self-sufficiency of the country. An Agricultural Drought Assessment and Monitoring System (ADAMS) system has been developed through cooperation between the National Remote Sensing Agency, the India Meteorological Department, the Central Water Commission, the Department of Agriculture and the governments of the States. The objective of ADAMS is to provide real-time information on agricultural drought conditions at the district level all over the country on a weekly basis using satellite remote sensing data supplemented by detailed ground data. A national survey will use NOAA AVHRR data to cover the entire country, while state systems will use higher-resolution

satellite data from Landsat, SPOT and the Indian Remote Sensing satellite (IRS). NOAA AVHRR data will be used to generate weekly or bi-weekly vegetation maps of the country though the agricultural season, using the normalized-difference technique. Identification of drought conditions will be based on converging evidence of anomalies in rainfall, aridity index and vegetation index, taking into account information on the planting dates of major crops.

71. Studies have also indicated that certain large-scale meteorological patterns are associated with the failure of the Indian summer southwest monsoon, which is the main cause of drought. Factors that can provide early indicators of possible drought include upper air winds over India, the development of hot low-pressure areas over southern Asia, and the El Niño/Southern Oscillation phenomenon in the Pacific Ocean. Other factors that can be observed by satellite and appear to be related to rainfall patterns are sea-surface temperature, snow cover, cloud patterns and atmospheric humidity profiles. If drought can be predicted in advance or identified early in the monsoon season, timely relief measures can be planned. Research is underway to identify more accurately the atmospheric, marine and land factors that correlate with drought conditions.

72. In irrigated land in arid areas, sand drifting onto cultivated fields and irrigation systems can reduce production. Sand dunes are generally easily recognizable on satellite images due to the very high reflectivity of sand at all wavelengths. In Egypt, where some 95 per cent of the land is desert, satellite images have been used to map areas where sands dunes are active and to identify places where the dunes are encroaching on agricultural land. Using visual interpretation of Landsat images from different dates, it was possible to identify the size and orientation of dunes and to estimate their direction and speed of movement in response to the prevailing winds. Maps of active sand dunes prepared in that way can assist in the planning of wind breaks or other structures to prevent or reduce the loss of arable land.

73. In Argentina, a comprehensive programme has been drawn up for using satellite data for environmental protection, including drought and desertification monitoring. The programme is starting with a statistical analysis of data for the past 15 years, including remote sensing and meteorological satellite data. That historical and baseline survey is to be followed by regular monitoring of land use, agricultural productivity and environmental changes for each of the arid and semi-arid regions in the country. The programme includes geological mapping, soil mapping, flood mapping, drought monitoring, land cover mapping and land degradation analysis. Automatic remote data collection platforms will relay, via the Geostationary Operational Environmental Satellites (GOES), ground measurements relating to rainfall, temperature, soil moisture, water levels in rivers and reservoirs, snow depth and other environmental variables.

74. The pressure on ecological systems in semi-arid areas depends on the population density and distribution, which may be quite variable and difficult to monitor. Satellite images have been used in a number of developing countries to determine the location and approximate size of human settlements. The settlements, even if consisting of only a few small habitations below the resolution of the sensor, will generally be revealed during the early dry season as clear patches

of harvested fields which are lighter than the surrounding dry vegetation and shrubs. The size of the cultivated area is a rough indication of the population of the settlement.

75. Environmental monitoring requires the integration of large volumes of remote sensing data with information from a variety of other sources. Handling the volume of data required and combining the different types of information can pose difficult practical problems. Furthermore, there is often no single optimum way to integrate the information from different sources and no single ideal map product that can meet the needs of different resource managers and planners. An important technique for integrating information from various sources in a flexible and interactive way is the computer-based geographical information system (GIS). The computer is programmed with a map base onto which geographic information from remote sensing systems or other sources can be entered. Historical data can be combined with current data to indicate trends and make future projections. The user can then combine the different information in various ways to provide answers to various management questions. An agricultural planning project, for example, might need to take into account information on soils, rainfall amount and seasonal distribution, topography, availability of irrigation water, existing land use, population density, administrative boundaries, and transportation and communication facilities. Information on these elements could be combined according to an agricultural economic model to produce a map of recommended land use for planning purposes. While GIS systems are complex and expensive to establish, once established they can quickly and inexpensively produce maps with land classified according to complex criteria specifically determined for the project in question.

C. Water conservation

76. The effective management of scarce water resources requires more or less continual assessment of the balance of rainfall, surface flow, infiltration and evaporation. In arid and semi-arid areas, what little rain there is often falls in brief but intense downpours, and in the absence of water conservation measures, the water will quickly run off into streams and rivers and be rapidly lost downstream. Collection of runoff in reservoirs and redistribution through canals and pipelines are important in providing water for development, including for human use, for livestock and for agriculture. Water storage and redistribution makes possible more effective use of water during the rainy periods and provides water during the dry periods.

77. Some of the rain that falls infiltrates into the soil, either absorbed into the upper metre or so and remaining available to plants, or draining into deeper layers where it may be available to wells. Mapping the distribution of soil moisture following rains can be an important input into agricultural planning and management for maximum use of limited water resources. Areas where soil moisture is retained may be indicated by relatively rich vegetation in otherwise dry areas. Microwave signals from satellite or aircraft systems penetrate the top layers of the ground surface, and the return signal is affected by soil moisture, so radar or passive microwave data in principle allows monitoring of soil moisture. Temperature measurements using thermal infrared or passive microwave sensors can also indicate soil moisture. In both of those applications, however, the influence of soil, vegetation, illumination angle and atmospheric effects complicate

the interpretation, and further research is needed before those techniques can become widely operational.

78. The runoff of rainfall, especially during heavy rain, can carry away topsoil and reduce soil fertility if soil conservation techniques are not practiced. Satellite multispectral data can be used to classify landscapes which are susceptible to water erosion and to map stream and river courses. High resolution imagery can be used for identifying areas of gully erosion. Sediment transportation by rivers into lakes or the sea is indicated by sediment plumes readily visible in the short-wavelength bands on multispectral scanners. Maps of erosion susceptibility can provide important information for planning land development while protecting soil fertility.

79. The management of water resources requires regular monitoring of water levels in lakes and reservoirs. Such surface water is generally easy to map using observations in the infrared band since water absorbs radiation in that band while the surrounding land, whether vegetated or bare, usually has a much higher reflectance. Even small streams or ponds that are too small to be seen on satellite imagery can usually be identified in arid and semi-arid areas by the relatively lush vegetation they support which appears prominently on false-colour images.

80. Many arid and semi-arid areas with very limited surface water resources have substantial groundwater deposits, sometimes dating from tens of thousands of years ago or more when the climate of the region was more humid. While ground water is not directly visible on satellite imagery, indications of geological structures that can accumulate and hold water are often visible. Large-scale linear features on images usually represent tectonic structures which affect drainage patterns, vegetation distribution and geomorphological features. Those features of the images can be interpreted to provide a map of fault lines and fracture zones that indicate where the prospects for finding ground water are best. Groundwater recharge and discharge areas can often be identified on the basis of vegetation patterns. Such techniques have been used in India to greatly increase the effectiveness of well-drilling programmes.

IV. CONCLUSIONS

81. Desertification is a complex phenomenon resulting from the interaction of climatic, geographic and human factors. None of those factors is very understood either theoretically or empirically, and none is easily modified. There is therefore a great need for further research and monitoring of desertification and experimental efforts to combat the problem. Space observations can play an important role in monitoring desertification processes, in mapping land potential for planning purposes, in monitoring the effects of land development efforts, and in improving our ability to understand and predict natural climate changes.

82. Desertification in developing countries is most often a response to urgent human needs for food and shelter. Desertification problems are generally due to a combination of rapid population growth, economic development efforts and natural climate variations. Effective measures to

combat desertification therefore must include measures to meet increasing human needs in ways that do not harm the environment. Research, development and education are needed to develop agricultural and land use practices that can increase productivity on a sustainable basis.

83. Problems of desertification are often common to a number of countries of a region with similar climate and natural resources. Those countries can therefore benefit by sharing their knowledge and experience in the fight against desertification. The development of new technologies for monitoring and for sustainable development will often be applicable in comparable climatic and vegetation zones throughout the world and can therefore be shared by many countries. All countries can therefore realize important benefits through international cooperation in the fight against desertification.

84. Climate change and global warming present new and unknown risks of desertification, both in existing arid and semi-arid areas and in areas that may become less humid. The current and planned research efforts, including the planned satellites designed for environmental monitoring, are important for understanding climate change and for developing plans to respond to potentially harmful changes.

85. The study of desertification requires consistent observations over long periods both in the past and in the future. Historical data, including satellite data gathered over the last 20 years, must be preserved and protected as an irreplaceable historical record. Continuity of the existing satellite systems is important both for continuing the collection of consistent and comparable data and to avoid costly replacement of existing data reception and processing systems, particularly in light of the financial difficulties in many developing countries in operating and maintaining such systems. Future satellite should be planned to provide systematic and consistent coverage of the entire world, both because virtually all countries are affected to some degree by desertification, and because some of the processes of desertification are global processes.

86. Long-term records of both climate and ground conditions are needed to distinguish between normal short-term variations and long-term trends, between changes that are readily reversible and those that are more permanent, and between changes due to climate and those due to human activities. A great deal of valuable research can be done at modest cost using the historical archives of satellite data.

87. While the existing multispectral remote sensing techniques offer powerful tools for studying and monitoring desertification, new techniques should also be explored. Satellite radar mapping systems, passive microwave sensors, and further development of thermal infrared applications all offer potentially important new tools for monitoring desertification.

88. It is important that the past, current and future satellite data relating to desertification be available to all countries at affordable prices. Since desertification is a particular problem for extensive areas of relatively low productivity, the cost of monitoring must be kept low if it is to

be economically viable. Consideration may need to be given to special pricing arrangements for data required for environmental protection in developing countries.

89. While satellite data is an essential tool for cost-effective monitoring of desertification, use of such data in developing countries is limited by a lack of sufficient people trained in remote sensing interpretation and with adequate image processing and interpretation equipment. There is therefore a great need for expanded training opportunities and technical assistance in the area of remote sensing applications to desertification. The new satellites, sensors, data processing techniques and information handling methods make the need for increased education and training more urgent if the potential of space technology for contributing to the fight against desertification is to be fuliy realized.

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